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S. C. Myers, C. A. Schultz

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THE USE OF IMPERFECT CALIBRATION FOR SEISMIC LOCATION

Stephen C. Myers and Craig A. Schultz
Lawrence Livermore National Laboratory

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ABSTRACT

Efforts to more effectively monitor nuclear explosions include the calibration of travel times along specific paths. Benchmark events are used to improve travel-time prediction by 1) improving models, 2) determining travel times empirically, or 3) using a hybrid approach. Even velocity models that are determined using geophysical analogy (i.e. models determined without the direct use of calibration data) require validation with calibration events. Ideally, the locations and origin times of calibration events would be perfectly known. However, the existing set of perfectly known events is spatially limited and many of these events occurred prior to the installation of current monitoring stations, thus limiting their usefulness. There are, however, large numbers of well (but not perfectly) located events that are spatially distributed, and many of these events may be used for calibration.

Identifying the utility and limitations of the spatially distributed set of imperfect calibration data is of paramount importance to the calibration effort. In order to develop guidelines for calibration utility, we examine the uncertainty and correlation of location parameters under several network configurations that are commonly used to produce calibration-grade locations. We then map these calibration uncertainties through location procedures with network configurations that are likely in monitoring situations. By examining the ramifications of depth and origin-time uncertainty, we expand on previous studies that focus strictly on epicenter accuracy. Particular attention is given to examples where calibration events are determined with teleseismic or local networks and monitoring is accomplished with a regional network.

Key Words: location, seismic regionalization, calibration

OBJECTIVE

We aim to analyze the utility and limitations of imperfect calibration data when applied to common monitoring situations. The most desirable set of calibration events would have little or no uncertainty in either hypocenter or origin time. However, such "perfect" calibration events are achieved through dedicated calibration explosions and the cost of developing a perfect calibration data set over a broad geographic region would be prohibitive. Therefore, a practical approach to the calibration of seismic location includes the use of events that are located with high – but not necessarily perfect – accuracy.

Highly accurate calibration events are generally earthquakes that are 1) well recorded with a regional to global network or 2) located to high accuracy with a dense local network. When the locating network is well distributed around an event, a high-accuracy location can be achieved, and these events can be used to calibrate travel times to permanent monitoring stations. However, even when the best network configuration is available, uncertainties in source location parameters can reduce calibration utility. We aim to track how uncertainties in earthquake ground-truth sources propagate through the calibration process, and identify limitations of using earthquake data for calibration.

RESEARCH ACCOMPLISHED

Accurate representation of calibration uncertainties includes mapping the uncertainty of calibration-event source parameters through the calibration process. This study examines how uncertainties and correlations in calibration-event location and origin time (we will refer to these parameters as source parameters) propagate through the calibration process. We begin by examining the correlation matrix for calibration-event source parameters determined with a regional to teleseismic network. We then examine calibration events that are located with a local network. An analytical expression for the propagation of source and travel-path uncertainties is derived, so that the importance of each term is identified. Additionally, an earthquake data set is used to empirically test the effect that location uncertainty has on calibration estimates. Of particular importance to this study are 1) the commonly noted correlation between event depth and origin-time parameters and 2) the way in which this correlation maps into travel-time calibration and subsequent seismic location.

Test Data Set

Throughout this study we refer to a test data set consisting of 111 events from the ISC catalogue. These events are recorded from regional to teleseismic distance and meet the criteria of at least 50 defining arrivals with a maximum azimuthal gap in station coverage of 90°. Sweeney (1998) found that events meeting these criteria are generally within 20 km of known locations. Some test events far surpass the above criteria and others barely meet the criteria. Furthermore, the events are geographically distributed throughout Eurasia and North Africa (Figure 1). Because this data set represents a wide range in station geometry and ray paths cover a diversity of tectonic provinces, location parameter uncertainties and correlations that are common to the test data set as a whole may be generally applied to other regional/global-network locations.

Trade off between event depth and origin time (regional/teleseismic network)

Common network configurations for monitoring and for the determination of calibration events include stations at regional to teleseismic distance. For monitoring, the set of stations is likely to be sparse (due to small source size) and for calibration the network is necessarily extensive (otherwise the above criteria are not met). The trade-off between event depth and origin time is evident from analysis of the location system of equations. The determination of earthquake locations is an inverse problem of the form:

$$Ax = r \qquad [1]$$

Where A is an Nx4 matrix of travel-time partial derivatives with respect to the four location parameters (N is the number of observations), x is a 4x1 vector of the change in location parameters, and r is an Nx1 vector of travel-time residuals. Equation [1] is a linearization of a non-linear problem, so [1] is iterated until a stable solution is found.

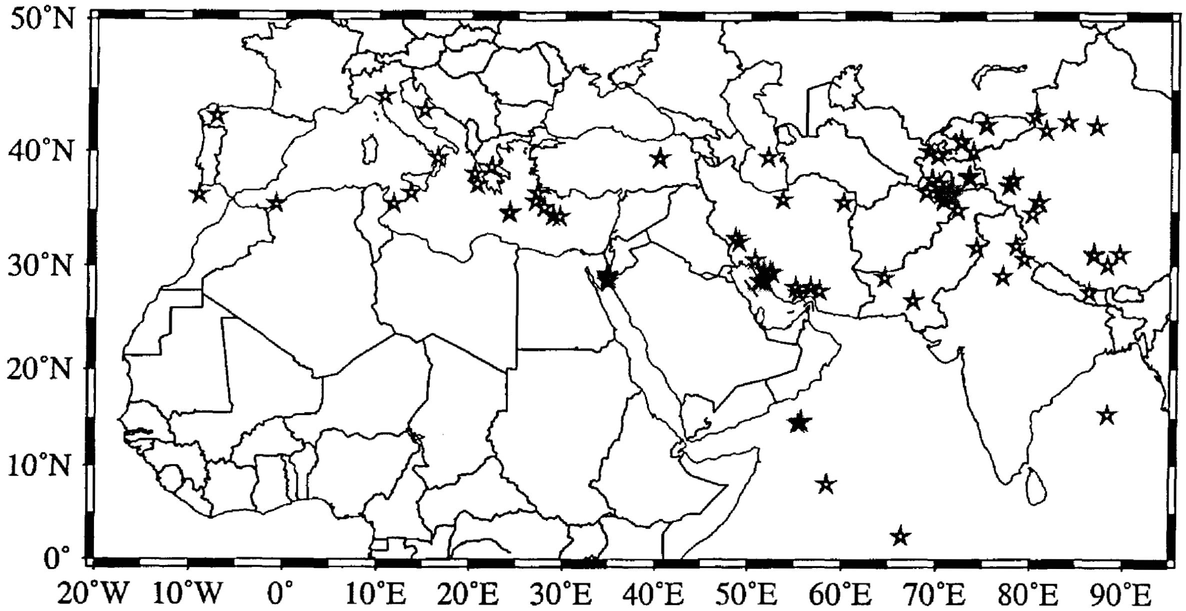

Figure 1. Epicenters of 111 test events are shown by stars. These globally recorded events meet the criteria of 50 defining phases and maximum azimuthal gap of 90°. In order to test how the trade-off between event depth and origin time effects calibration, travel-time residuals are calculated for test events with depths fixed at 0 and at 30 km. The depths reported in the ISC catalogue range from 0 to 174 km.

For events located with a regional to teleseismic network, the resolution of event depth and origin time parameters is poor. Figure 2 shows the average A martix for 111 test events. The pertinent features of Figure 2 are that partial derivatives for the horizontal components of event location are widely varying and uncorrelated, whereas the partial derivatives with respect to event depth are nearly identical for each arrival. Because the vertical partial derivatives are nearly constant and partial derivatives for origin time are always equal to one, the column vectors of partial derivatives representing depth and origin time are nearly linear combinations of one another. Therefore, there will be little resolution between origin time and event depth. The correlation between source parameters is further investigated by computing the model correlation matrix for the average A matrix (Figure 3). Again, the horizontal components of location are uncorrelated with other source parameters, whereas origin time and depth are almost perfectly correlated.

It is important to note that the above analysis does not include depth phases. Of the crustal events in the test data set, depth phases were not identified in the International Seismic Center (ISC) catalogue. Because depth phases are rarely identifiable as distinct arrivals for crustal events at regional to teleseismic distance, we believe that this analysis is representative of both calibration and monitoring situations for which local data are not available. We note that some subcrustal events are included so that a broad range of true event depth is considered.

Origin-time bias (local network)
Locations derived from a local network, such as an aftershock study, can have well-determined hypocenters with uncorrelated depth and origin-time parameters. Because of this superior hypocenter accuracy, these events are highly desirable for calibration of monitoring stations. Although existing hypocenters determined with a local network do not provide the spatial coverage afforded by events determined with regional to teleseismic networks, these events can provide important high-accuracy calibrations at specific geographic locations.

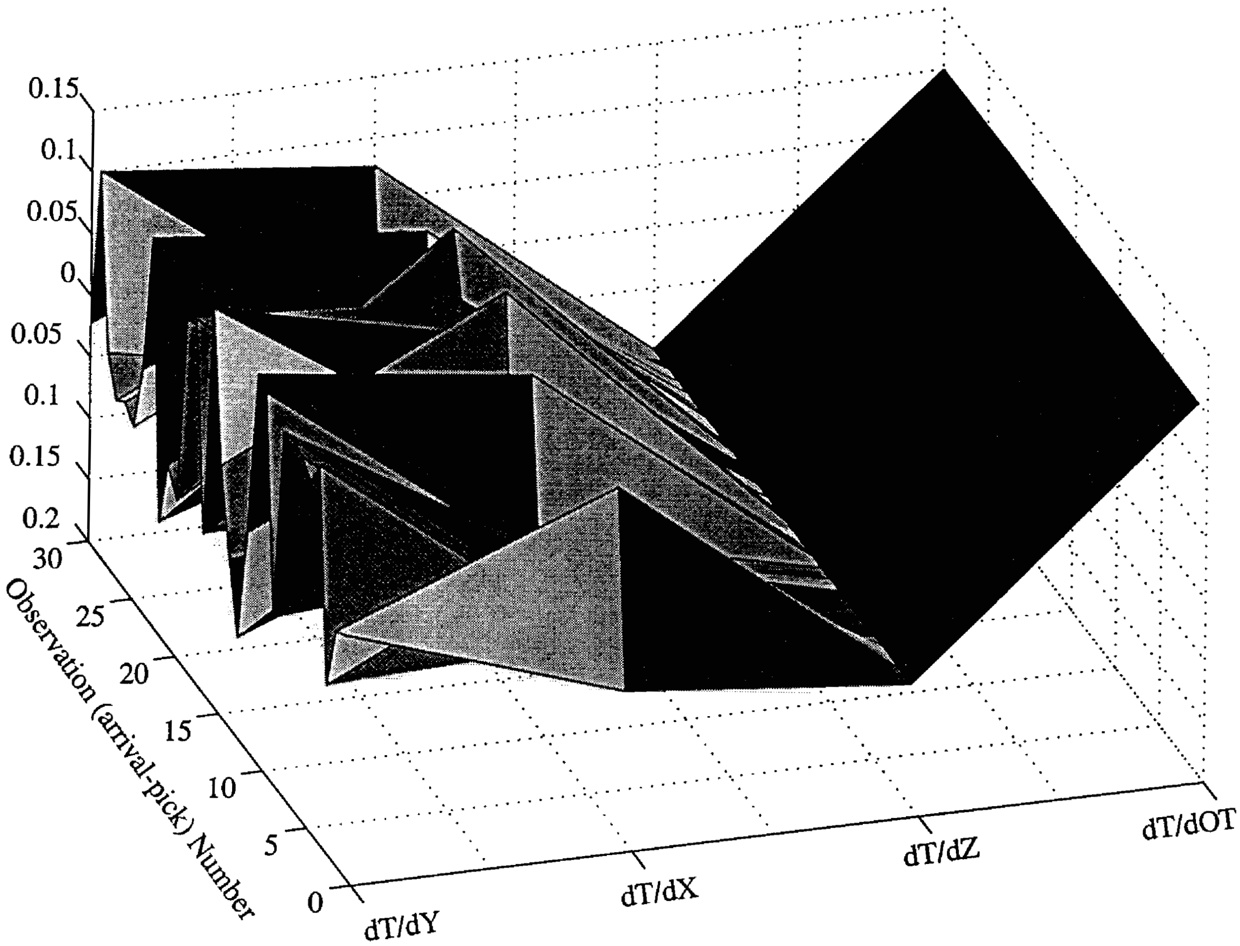

Figure 2 Partial derivative matrix for a typical event located with a regional to teleseismic network. Note that the partial derivatives with respect to depth (Z) and origin time (OT) are nearly linear combinations of one another, so there will be little or no resolution between depth and origin time. The number of observations is cut to 30 and the values of the origin-time partial derivatives are scaled down from their value of 1, so that matrix features are clear. See text for discussion.

Unfortunately, origin times for events determined with local networks are not beyond reproach. The most significant source of origin-time error can be systematic travel-time prediction errors due to velocity model inaccuracies. Several studies demonstrate that origin times for events located with a local network can be biased by systematic travel-time prediction errors (e.g. Pavlis, 1986), even when a "best estimate" of local velocity structure is used.

The consequence for calibration is that origin time bias is directly mapped into travel-time corrections (i.e. residuals). If a bias between observed and predicted travel time is well resolved (i.e. origin time bias is minimal), then an overall bias between observed and predicted travel-times is important calibration information. However, because the magnitude of the origin-time bias is unknown for most local studies, we may inadvertently propagate origin-time bias into calibrations by using origin times from local studies.

To further complicate matters, origin-time bias is likely to change from locale to locale. If the bias for one aftershock study is not the same as a neighboring study, then travel-time corrections derived from the two locales

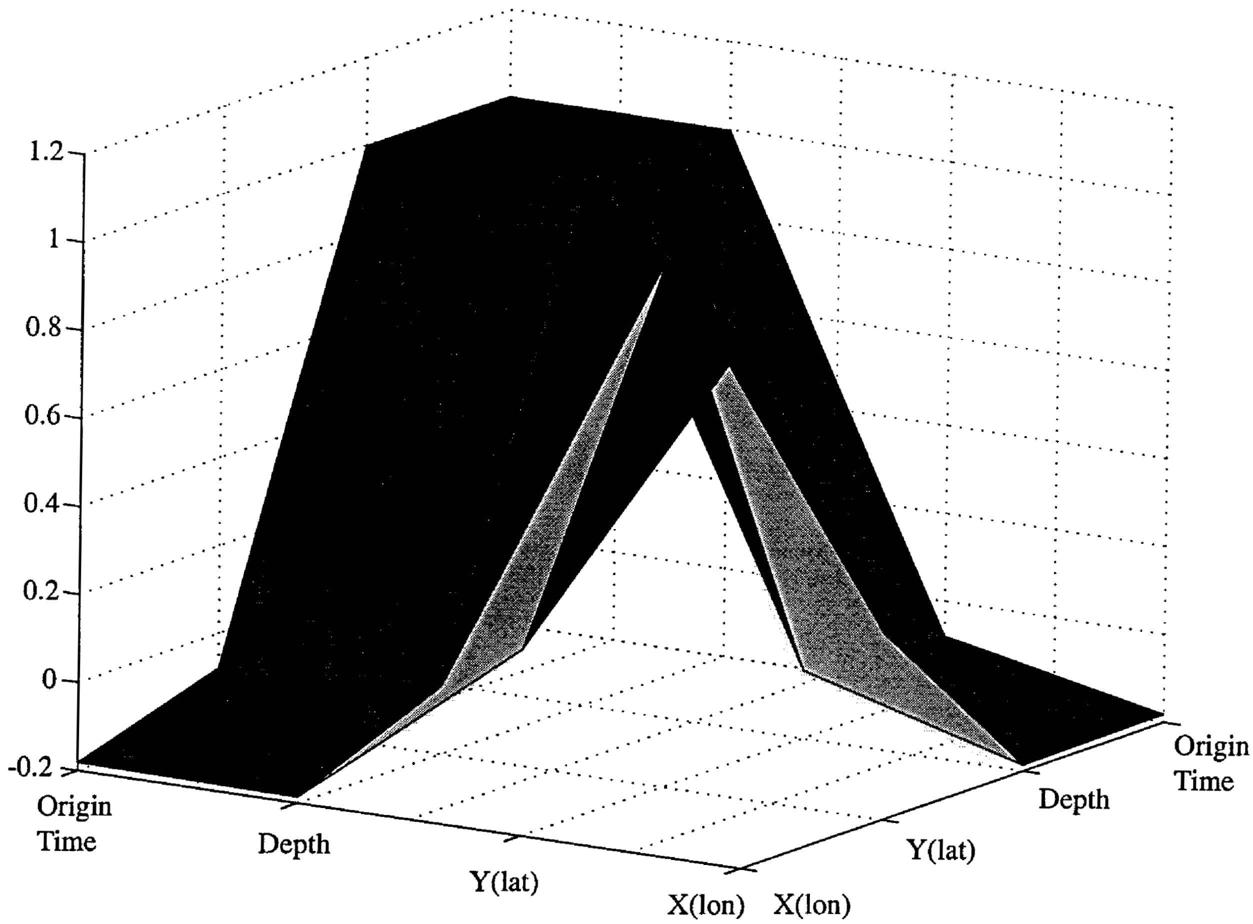

Figure 3
Averaged model correlation matrix for 111 events determined with a regional to teleseismic network. Horizontal components of event location are not significantly correlated with other parameters, whereas, the correlation between event depth and origin time is almost perfect. The correlation matrix demonstrates the trade-off between origin time and depth.

will not be compatible. When viewed as a geographic surface of travel-time residuals, there will be a discontinuity between the two local studies. In other words, combining local studies with differing origin-time biases results in geographically non-stationary calibration bias.

One way to insure a zero-mean origin-time residual (remove origin-time bias) is to fix the hypocenter -- as determined with a local network -- and recalculate the origin time relative to the velocity model that is to be calibrated. However, numerous regional to teleseismic stations must be used, and the local stations must be omitted when determining the new origin time. If local stations are included, then bulk differences between the crustal portion of the regional velocity model and each local velocity structure will again result in non-stationary origin-time bias. As discussed above, when the local stations are removed there is almost perfect correlation between origin time and depth. Therefore, even though the new origin time is not biased, it is not well resolved and a strong trade-off between origin time and event depth persists.

From the above discussion it would appear that origin time is difficult to pin down. Because the travel-time residual is the observed arrival time minus the sum of origin time and predicted travel time, it is not obvious how travel-time calibration can be derived from earthquake data sets.

How important is it to resolve the origin-time and depth of a calibration event?
Travel-time calculation is separable into vertical and horizontal components. The basic travel-time equation for a surface focus in a layered media is

$$t = Xp + 2\sum_{i=1}^{N} h_i \eta_i \qquad \eta_i = \left(1 - v_i^2 p^2\right)^{1/2} / v_i \qquad [2]$$

where t is travel time, X is horizontal distance, p is ray parameter (horizontal slowness), h_i is the thickness of each layer, η_i is vertical slowness, v_i is the velocity of layer i, and N is the number of layers from the surface to the bottoming depth of the ray. There are direct analogies to continuous velocity structures, but we present the discrete case for simplicity. For a non-surface focus, layers entirely above the focus only contribute once to the vertical slowness component (the up-going ray) and the layer containing the event contributes once for the up-going ray with a fractional contribution to account for the path from the focus to the bottom of the layer.

In order to isolate the effects of various portions of the travel path and calibration event parameters, we derive the variance of the travel-time residual by substituting a two-layer velocity model (equation [2]) into the travel-time residual equation ($t_{res}=t_{observed}-t_{predicted}$). We then expand the square of the right-hand-side of the resulting equation. Because the expected value of the travel-time residual is zero (re-computing the origin time forces the average residual to be zero) the distribution of the travel-time calibrations is described by the variance of the travel-time residuals. From the previous section we know that the only correlated source parameters are origin time and depth, and from equation [2] we see that event depth only affects the vertical component of travel time. Therefore, we find that the only correlated parameters in the travel-time residual equation are those for event depth, event origin time, and the vertical component of travel time, and the variance of t_{res} reduces to:

$$\sigma_{res}^2 = \sigma_{t_o}^2 + \sigma_X^2 + \sigma_z^2 + \sigma_O^2 - 2\rho_{Oz}\sigma_O\sigma_z \qquad [3]$$

where σ^2_{res}, σ^2_{to}, σ^2_X, σ^2_z, σ^2_O are variances for the travel-time residual, arrival-time pick, horizontal travel time, vertical travel time, and origin time, respectively, and ρ_{oz} is the correlation coefficient between origin time and the vertical travel time. We know from the previous section that ρ_{oz} is approximately one. Therefore, if σ_z and σ_O are equal, then uncertainty in depth and origin time have no effect on the travel-time residual (calibration) distribution. Although σ_z and σ_O are generally not equal, the last term of equation [3] will tend to minimize the effect of event origin time and depth errors on the travel-time residual.

We empirically test the importance of event depth using the aforementioned test data set. The best origin time is determined with each epicenter fixed at the ISC epicenter and event depth set to zero. This procedure is repeated with event depth set to 30 km.

Figure 4a,b shows the distribution of the absolute value of the mean travel-time residual for each event when event depth is set to 0 and 30, respectively. So each occurrence in the distributions shown in Figure 4a,b is the mean absolute value of travel-time residuals for one event. We note that the sum of the squared errors is approximately equal for each event when depth is fixed at the surface and 30 km, so neither depth is necessarily preferred by the data. To make Figure 4c we first compute the difference between travel-time residuals at each station for a single event. For each event we find the average of the absolute value of these differences, and Figure 4c is the distribution over all events.

Figure 4c shows that on average, the expected difference in travel-time residual resulting from fixing the depth of an event at a grossly incorrect depth is about 0.34 seconds. The maximum computed error for the same scenario is 0.62 seconds. Considering that the calculated difference in travel time between a surface and 30-km-depth event is about

3.3 seconds (6 km/s crust), these results support the analytically derived prediction that correlation between origin time and event depth will tend to negate errors in depth. Comparing Figure 4c to Figures 4a,b, it is evident that errors resulting from incorrect event depth are a small component (~20%) of the overall residual distribution; the mean value of the distributions in Figure 4a,b are 1.81 and 1.72 seconds, respectively, compared to a mean value of 0.34 seconds resulting from different event depths.

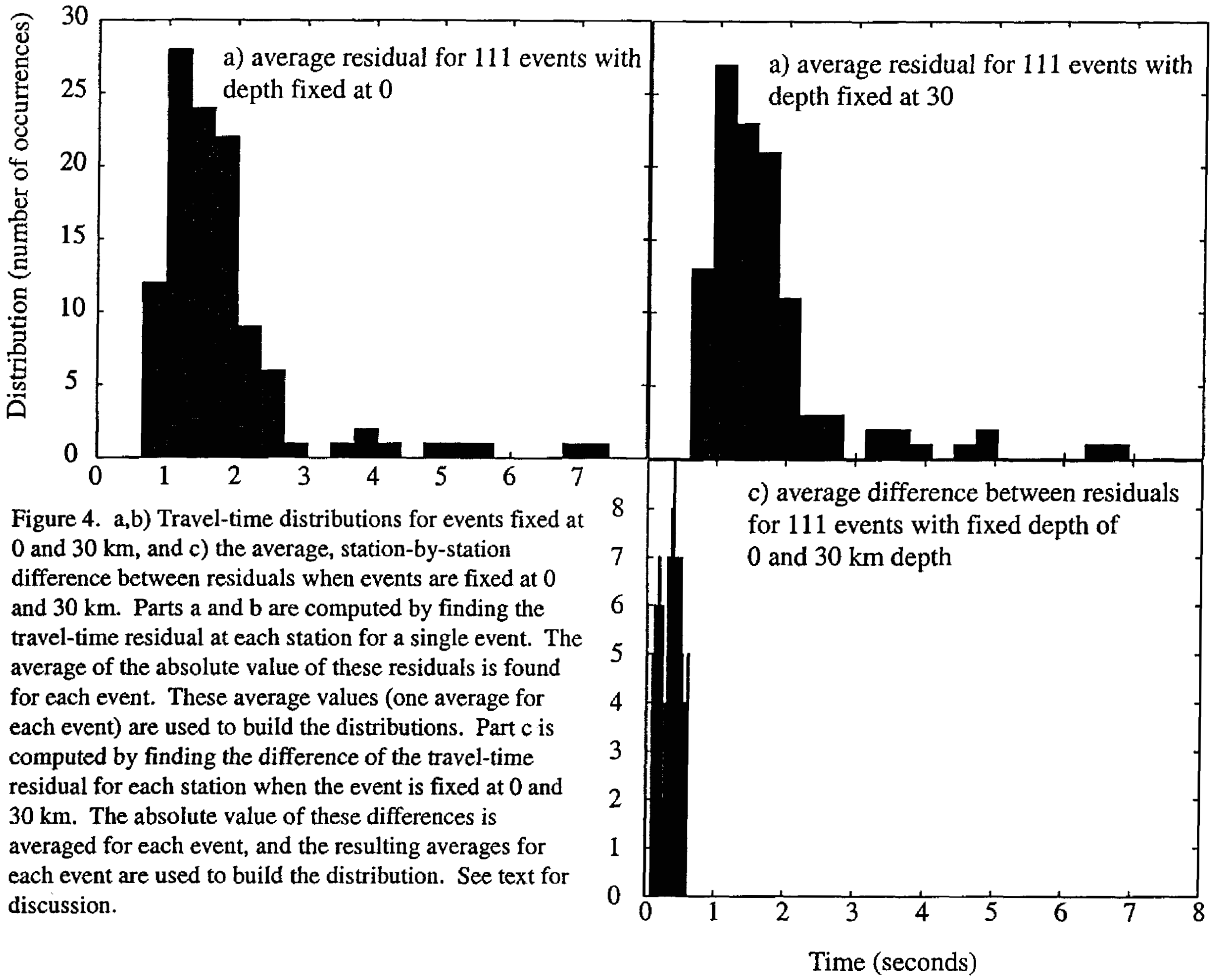

Figure 4. a,b) Travel-time distributions for events fixed at 0 and 30 km, and c) the average, station-by-station difference between residuals when events are fixed at 0 and 30 km. Parts a and b are computed by finding the travel-time residual at each station for a single event. The average of the absolute value of these residuals is found for each event. These average values (one average for each event) are used to build the distributions. Part c is computed by finding the difference of the travel-time residual for each station when the event is fixed at 0 and 30 km. The absolute value of these differences is averaged for each event, and the resulting averages for each event are used to build the distribution. See text for discussion.

Another component of the residual distribution is picking error. Under the best circumstances, the standard deviation of picking error is about 0.25 seconds for first arrivals, and more typically the standard deviation of picking error is 0.5 to 1.0 second (F. Ryall, personal communication). Therefore, errors introduced by calibration-event depth inaccuracies are likely to be less than picking error. Only when picking error is small does the variance of picking and event-depth error become approximately equal.

Separability of calibration into vertical and horizontal slowness

From the calibration standpoint, it is the correction of model errors that we would like to extract from the travel-time residuals. Commonly, travel-time residuals for a well-recorded event have a structured spatial (geographic) pattern, although incoherent noise from random processes like picking error can blur the pattern. It is the underlying spatial pattern that represents the systematic travel-time error due to velocity-model inaccuracies. Techniques such as non-stationary Bayesian kriging (Schultz et al., 1998) are demonstrated to effectively extract model error from a spatially distributed set of travel-time residuals (Myers and Schultz, 2000). However, given the trade-off between origin time and depth, we would like to know just what we are calibrating when we extract model error from the pattern of earthquake travel-time residuals.

From the correlation between the vertical component of travel time and event origin time (Equation [3]), it is clear that recalculating the origin time absorbs much of the near-event model inaccuracy in vertical slowness. Physically, we interpret this finding to mean that near-source velocity anomalies and errors in event depth have the effect of slowing or advancing seismic arrivals at regional to teleseismic stations by approximately the same amount of time. In the location process, equally shifting the time of all network arrivals maps into a change in origin time. Conversely, Equation [2] shows that the variance in horizontal slowness is not diminished by correlation with other parameters. So, neither origin time nor other source parameters can absorb inaccuracies in horizontal slowness. Therefore, we conclude that near-source vertical slowness anomalies and errors in event depth play a minimal role in affecting the spatial (geographic) pattern of travel-time residuals, and the dominant parameter affecting the spatial pattern of regional travel-time residuals is variations in horizontal slowness from the base velocity model.

CONCLUSIONS AND RECOMMENDATIONS

Spatial coverage of travel-time calibration events can be vastly improved if earthquakes are used to augment the catalogue of explosion sources. Unlike dedicated calibration explosions, source parameters of earthquakes are not perfectly known. Although earthquake source-parameter uncertainties present some limitations, we find that useful calibration information can be extracted from earthquake data sets.

The origin times and depths of earthquake calibration events are typically poorly known, and a strong correlation between origin time and depth exists. In contrast, event latitude and longitude are typically well resolved, and these horizontal location parameters are not correlated with other source parameters. As a result, earthquake data sets are most useful for calibrating horizontal slowness. This is fortunate, because horizontal slowness is the critical parameter in most monitoring situations. Because clandestine tests are unlikely to occur near a local network, depth estimates will rely on surface reflections, and surface reflections are not likely to be separable from the direct pulse for a shallow event. Unfortunately, the absence of surface-reflected waves cannot be used as evidence for a surface focus, and a location based on sparse regional recordings will be poorly resolved in depth. Poor vertical resolution commonly requires event depth to be fixed during the solution of source parameters, and when event depth is fixed, calibration of horizontal slowness becomes far more important than calibration of vertical slowness.

Although the depth of calibration events can be well constrained by using a local network, event origin time can remain suspect due to systematic local-velocity-model inaccuracies. Furthermore, the origin-time bias is generally different for each local study. Local studies can be tied together by re-computing origin times using arrivals from regional to teleseismic stations. However, local stations must be removed from this process (see above), resulting in diminished resolution of near-source vertical slowness calibration. We note that similar origin time issues arise when origin times for nuclear explosions with perfectly known hypocenters are estimated using seismic arrivals. Based on the empirical difference of travel-time residuals for events that are fixed at different crustal depths, we find that using accurate event depth information can account for as much as 20% of a typical travel-time correction. Therefore, if both excellent depth resolution of calibration events is available and the monitoring network and recorded phases provide resolution of event depth, then use of 3-dimensional travel-time corrections can have utility.

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